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Integration of biomass fast pyrolysis and precedent feedstock steam drying with a municipal combined heat and power plant

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ABSTRACT

Biomass fast pyrolysis (BFP) is a promising pre-treatment technology for converting biomass to transport fuel and in the future also for high-grade chemicals. BFP can be integrated with a municipal combined heat and power (CHP) plant. This paper shows the influence of BFP integration on a CHP plant's main parameters and its effect on the energetic and environmental performance of the connected district heating network. The work comprises full- and part-load operation of a CHP plant integrated with BFP and steam drying. It also evaluates different usage alternatives for the BFP products (char and oil). The results show that the integration is possible and strongly beneficial regarding energetic and environmental performance. Offering the possibility to provide lower district heating loads, the operation hours of the plant can be increased by up to 57%. The BFP products should be sold rather than applied for internal use as this increases the district heating network's primary energy efficiency the most. With this integration strategy future CHP plants can provide valuable products at high efficiency and also can help to mitigate global CO_2 emissions.

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1. Introduction

The reduction of CO_2 emissions and increasing independency in energy supply leads to more sustainable use of local and renewable energy sources. For instance, EU directives on the promotion of cogeneration (2004/8/EC) and on the promotion of energy from renewable sources (2009/28/EC) demand for efficient and sustainably increased utilisation of biomass for energy and transport purposes.

In Finland, apart from use in the wood and pulp & paper industry, lignocellulosic biomass is mainly used for heat and power generation. Biomass-based combined heat and power (CHP) production or cogeneration is an established and efficient technology that has proven to be competitive with conventional energy generation under current tax regimes that account for the high CO_2 emissions related to fossil fuels. However, increased use of biomass will raise the prices for limited biomass feedstock in the future and might hamper the economy of municipal biomass-fired CHP plants. Fig. 1a shows a typical heat duration curve of a district heating (DH) network under Nordic conditions. It can be observed that full load operation of the plant is only possible on approximately 70 days of the year; the plant will be operated under less

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Abbreviations: BFP, biomass fast pyrolysis; CHP, combined heat and power; DH, district heating; PE, primary energy.

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Nomenclature

q_a	daily district heat demand after calculated load variation [MWh]
q_i	daily district heat demand initial value [MWh]
x	number of the day on the heat duration curve [–]
η_{tot}	overall efficiency
f	primary energy factor [–]
Q	heat (district heat or fuel heat on lower heating value-base) [MW]
P	electricity [MW]
BM	biomass
FO	fuel oil

efficient part load conditions during 145 days per year and will be shut down eventually for about 150 days which clearly exceeds the time required for yearly maintenance. In other words such plants offer a huge potential of available boiler capacity that could supply heat for thermo-chemical conversion processes, such as gasification or pyrolysis. In such concept the heat required for the thermochemical conversion would be supplied by the fuel boiler and low-grade heat potentially rejected at the cold end of the conversion process could be utilised in the DH network, thus increasing the overall efficiency. Such integration would bear the potential of increasing the boiler capacity utilisation and adding an additional biomass product to the plant portfolio, which could increase the competiveness and allow CHP plants to be a part of the currently establishing bio-economy.

Biomass fast pyrolysis (BFP) is the thermal conversion of preferably dry biomass in the absence of oxygen at temperatures of approximately 500 °C and atmospheric pressure. It yields a mixture of approximately 13 wt-% non-condensable gases (mainly, CO and CO_2), 75 wt-% pyrolysis oil (incl. water) and 12 wt-% solid char. The fast pyrolysis process requires approximately 15% of the feedstock energy for providing the heat for the endothermic fast pyrolysis process (BFP requires heating up the biomass to reaction temperature and heat for the actual decomposition reactions) and thus has a high energetic efficiency as all products can be energetically used within the process [1].

Available reactor technologies for BFP have been recently reviewed and research units comprise mainly of the fluid bed type (bubbling and circulating). However, regarding industrial application, also screw feeder driven reactors are applied [1,2].

Most recently, Fortum OY started operation of the world's first industrial BFP unit producing 50 kt/year of pyrolysis oil in Joensuu, Finland. In this plant, the BFP process has been integrated with a municipal CHP plant, but neither the influence on the power and heat generation nor on the part-load behaviour has been reported yet. Fast pyrolysis occurs in a circulating fluidised bed reactor with heat transferred by sand

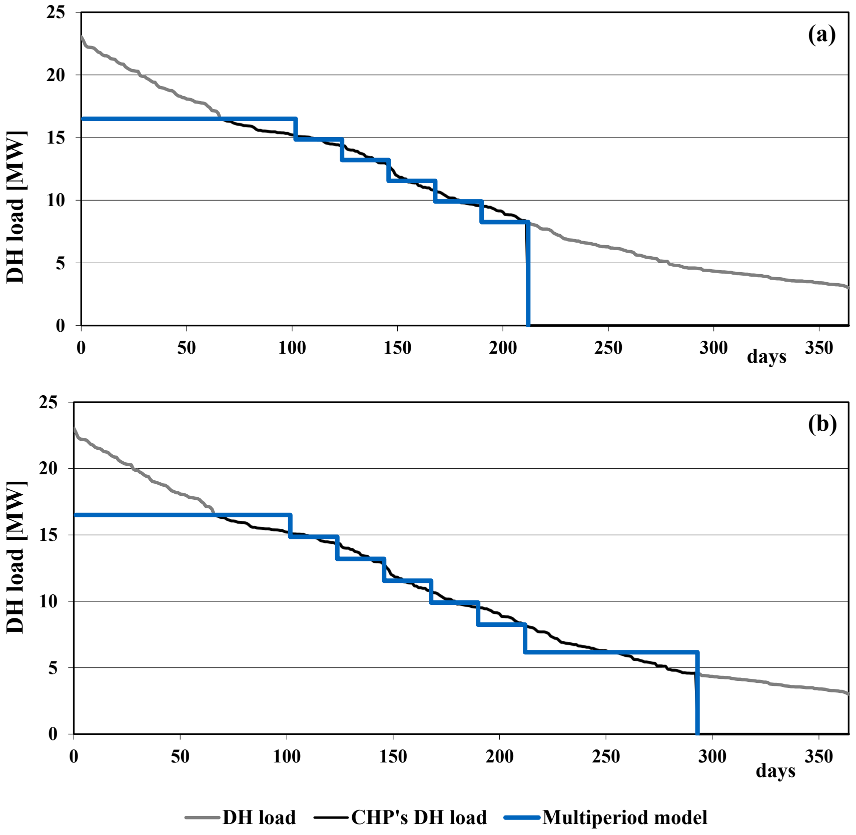

Fig. 1 – **Heat duration curve and DH load multiperiod model (a) Stand-alone CHP plant and (b) integrated case with subload.**

taken out from an interconnected bubbling fluidised bed combustor. The hot pyrolysis gases are separated from sand and char in a hot cyclone and char and sand are recycled to the combustion reactor. After quenching with cooled pyrolysis oil the non-condensable gases are combusted in the boiler. The oil will be used partly in company's own heating plants and partly will be sold to another energy supplier to also replace heavy and light fuel oil.[1] Combustion of unblended pyrolysis oil was recently found to be well possible in industrial heating boilers equipped with specially designed burners with all parts in contact with the acid pyrolysis oil made out of stainless steel [3].

Another successful application of the BFP process is the bioliq® process patented by the Karlsruhe Institute of Technology (KIT). BFP takes place in a twin-screw reactor in where biomass and hot sand are mixed. The hot sand provides the heat for the pyrolysis reaction in where it cools down from approximately 550 °C to 450–500 °C, depending on the sand-to biomass ratio which is typically in the range of 1:10–1:20 [personal communication R. Stahl, KIT, 2009]. The hot pyrolysis gases and the majority of the char leave the reactor and are separated in a hot cyclone and the sand is recycled to a reheater that could be fired with the non-condensable pyrolysis gases [4].

Pyrolysis of straw yielded 55 wt-% of pyrolysis oil (incl. water) [4], but higher values of about 68 wt-% liquid yield have been reported earlier for wood feedstock [5]. Within the bioliq® approach the liquid pyrolysis is re-mixed with the char product (forming so-called pyrolysis slurry) and supplied to an entrained-flow gasifier for syngas production and subsequent production of DME (dimethylether) and further synthesis with methanol to gasoline [4]. According to the bioliq® website (www.bioliq.de, August 2014) the whole process chain consisting of BFP, gasification, gas cleaning and DME synthesis and gasoline synthesis is in operation, but detailed process data has not been reported yet.

Also Green Fuel Nordic OY is starting to build a stand-alone BFP unit in Iisalmi, Finland, with an output of 90 kt/year of pyrolysis oil.[2] Two additional plants are planned.

In The Netherlands, EMPYRO has started to build a 25 kt/year BFP demonstration plant at Hengelo.[3]

Apart from use of pyrolysis oil in fuel oil boilers, it could be used in gas turbines and internal combustion engines for CHP production but so far long-term demonstration has not yet been achieved [6]. The production of gasoline after thermal gasification of pyrolysis slurry has been proven on pilot-scale by KIT as described above. According to [1], no research activities have been reported since 2010 for other upgrading technologies aiming for the production of hydrocarbons, chemicals and improved bio-oils and the author concluded that much of the research is still at a fundamental scale and that the most interesting activities would require larger-scale application in order to prove feasibility and viability. Woolf et al. [7] pointed out the potential for CO_2 mitigation when pyrolysis char is sequestered.

When stored, pyrolysis oil shows some ageing due to chemical and thermal instability due to its high content of reactive oxygenated hydrocarbons. An overview on the different ageing mechanisms can be found in Ref. [8], and ageing mainly leads to higher viscosity and lower heating values. Adding ethanol or methanol will stabilise pyrolysis oil under ambient conditions [8]. Also lowering the storage temperature can avoid the ageing problem [9]. KIT states that after separation of char and two-stage condensation which separates the pyrolysis oil in a water-rich and tar-rich phase, ageing does not impede the quality of the produced bio-slurry [4].

It is generally acknowledged that complex upgrading facilities will need to be built in large-scale (100 MW thermal or more) due to the economics of scale and that pyrolysis oil or –slurry that is produced in local or regional units would allow economically viable transport to those [1,4,10]. When integrated with BFP, such local CHP plant environments could provide the infrastructure and the biomass resources at low transport distances in order to produce energy-dense pyrolysis oil or -slurry suitable for transport to and utilisation in large-scale facilities. As pointed out above, pyrolysis oil has the potential to become a valuable inter-stage product suitable for multiple upgrading processes and CHP plants could benefit from the developing product demand. By producing pyrolysis oil or –slurry CHP plants could start producing a valuable inter-stage product that can already be used today, without being dependant on future upgrading pathways.

Regarding the integration of biomass upgrading with power and heat applications, the current work has mostly been related to biomass gasification. Although, Wahlund et al. [11] showed that an existing integration of pellet production with a municipal CHP plant results in longer operation hours and better environmental and economic performance of the related energy system. Integration of large-scale biomass gasification with a CHP-based DH system has potential to decrease net CO_2 emissions and to increase profitability [12,13]. Integration of synthetic natural gas production with a biomass CHP plant has been found technically feasible by Heyne et al. [14]. Eriksson and Kjellström [15] concluded that wood-based ethanol production is most feasible when integrated with a CHP- or combined cycle plant and Starfelt et al. [16] stated that retrofit integration of a CHP plant with bioethanol refining increases operation hours, electricity production and system efficiency.

Part of the work mentioned above, analyses only design case operation [12–15], or only one or two additional load points [11,16] are considered. Hence the part load operation and its mutual influence with the integration concept, especially on the operation parameters of the steam side has not been studied in detail. In addition, the influence of the integration of BFP on the DH network connected to a municipal CHP plant has not been analysed.

The objective of this work is to simulate the retrofit integration of the BFP process with a small- to medium-scale (up to 30 MW thermal) municipal biomass CHP plant by using the free boiler capacity in part-load operation for biomass drying and subsequent pyrolysis. The given DH load of the connected

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[1] http://www.fortum.com/en/mediaroom/pages/fortums-bio-oil-plant-commissioned-in-joensuu-first-of-its-kind-in-the-world.aspx, August 2014.

[2] http://www.greenfuelnordic.fi/en/page/23?newsitem=10, August 2014.

[3] http://www.empyroproject.eu/, August 2014.

Table 1 – Wood fuel properties and CHP plant design data (M: moisture).

Wood fuel properties					CHP plant – design data			
Ultimate analysis: dry basis [wt.%]	C	50.64	Ash	0.8	Fuel input	24.7 MW	Power output	5.21 MW
	H	6.1	M	50	DH output	16.5 MW	Condenser pressure	1.55 bar
	O	42.22			Live steam	60 bar/510 °C		
	N	0.16	LHV [MJ/kg]	7.89	DH supply temp.	110 °C	DH return temp.	83 °C
	S	0.08						

network will be fully retained at maximum BFP product output. It is anticipated that within the operational limits of the CHP plant considerable amounts of biomass can be converted to valuable pyrolysis oil or slurry and that the yearly operation hours of the CHP plant can be extended as described in Ref. [11].

The critical process parameters are identified and analysed and indicate in which parts of the process further improvement can be achieved by adjustment of those. A multiperiod load model of the DH network is applied to calculate and compare the network's yearly fuel and load characteristics. Based on this analysis the DH network's energetic and environmental performance is assessed based on primary energy (PE) factors and the estimated avoided CO_2 emissions. As the DH load forms a critical input to the simulation model, the multiperiod model has been altered in order to represent annual load variations. As a novelty, different internal and external usage pathways of the BFP product fractions (pyrolysis oil and char) are evaluated regarding their energetic and environmental performance.

Summarising, pyrolysis is an emerging technology close to industrial-scale application and it is suitable for integration with CHP plants. This paper investigates in how far the benefits known from other biomass conversion integration

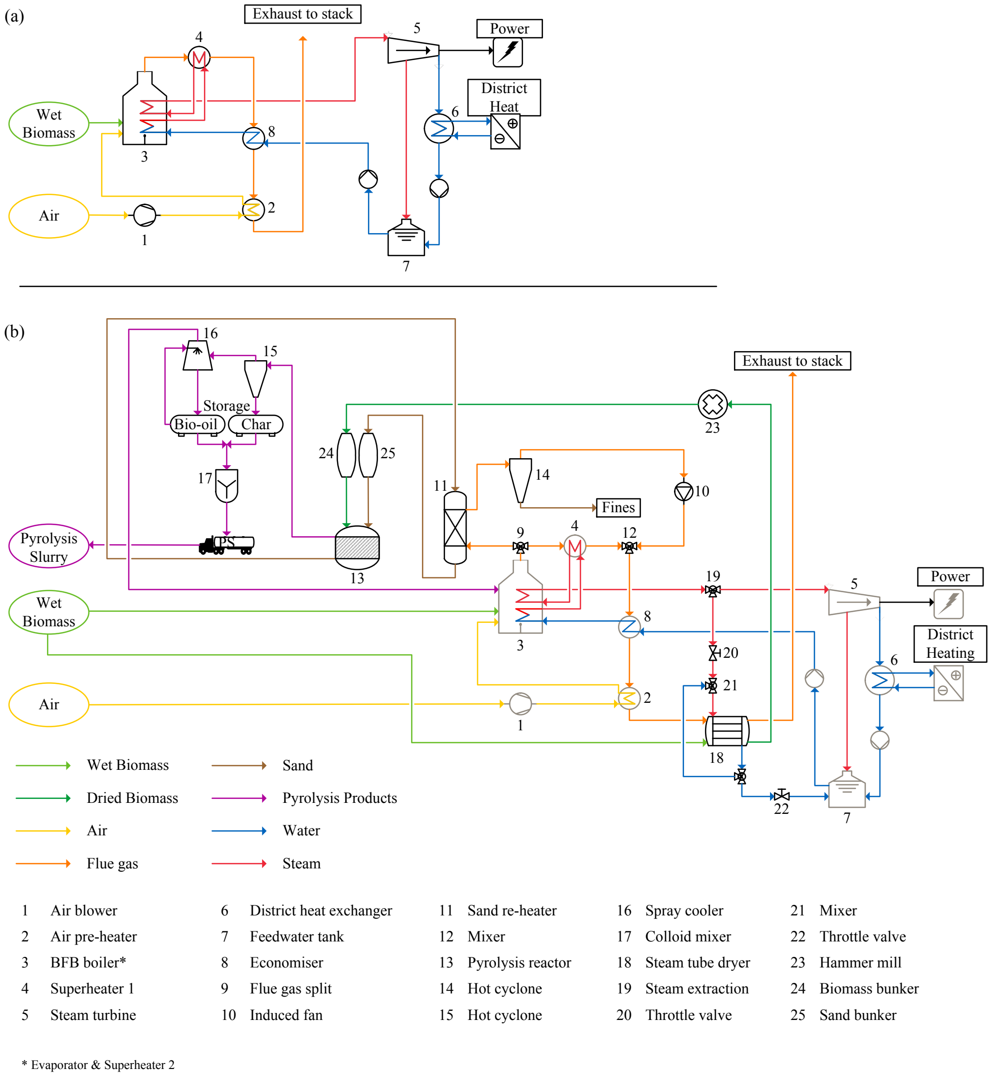

Fig. 2 – Process layout for (a) stand-alone CHP-plant and (b) CHP plant integrated with steam drying and BFP.

Table 2 – BFP model components.

Group	Component	Formula	Starting value [g]	Estimated value incl. moisture [g]
Gas	Carbon monoxide	CO	83.35	68.40
	Hydrogen	H_2	7.47	6.95
	Methane	CH_4	0.44	0.41
	Carbon dioxide	CO_2	68.87	56.51
	Ethane	C_2H_6	1.80	1.72
	Propane	C_3H_8	1.93	1.84
	Ammonia	NH_3	1.94	1.73
	Hydrogensulfide	H_2S	0.85	0.75
	Total gas		**166.66**	**138.31**
Phenols	Phenol	C_6H_6O	4.73	4.52
	Guaiacol	$C_7H_8O_2$	8.15	6.68
	m-cresol	C_7H_8O	7.62	7.26
	1,2 Benzenediol	$C_6H_6O_2$	11.35	9.32
	Vanillin	$C_8H_8O_3$	6.75	5.53
	Total phenols		**38.59**	**33.31**
Acids	Formic acid	CH_2O_2	62.35	51.16
	Acetic acid	$C_2H_4O_2$	59.66	48.96
	Propionic acid	$C_3H_6O_2$	4.01	3.29
	N-Butyric acid	$C_4H_8O_2$	13.66	11.22
	Glycolic acid	C_2H_4O3	7.19	5.90
	Total acids		**146.88**	**120.53**
Aldehydes	Formaldehyde	CH_2O	46.45	38.12
	Hydroxyacetaldehyde	$C_2H_4O_2$	71.05	58.30
	Glyoxal	$C_2H_2O_2$	14.52	11.91
	Acetol	$C_3H_6O_2$	56.95	46.73
	Butanol	$C_4H_{10}O$	29.15	23.92
	Total aldehydes		**218.12**	**178.98**
Sugars	Glucose	$C_6H_{12}O_6$	72.84	59.77
Lignin	Pyrolitic lignin	$CH_{1.1}O_{0.3}$	131.22	107.68
Water	Water	H_2O	59.03	154.16
Char	Char	$CH_{0.48}O_{0.23}$	166.66	138.50
Hydrocarbon	Pyrene	$C_{16}H_{10}$	–	61.61
Ash	Ash	–	–	7.15
Total			1000	1000

concepts will apply for BFP integration with municipal CHP plants. By more detailed part load modelling, it will provide insight on the thermodynamic feasibility of the integration as such but will also reveal the effect on the connected DH network.

2. Methodology

Based on full- and part load simulation models of a municipal stand-alone CHP plant (case CHP), simulation models of biomass steam drying and BFP were added to the stand-alone CHP plant simulation models. A sensitivity analysis was carried out in order to prove the correctness of certain assumptions and the improvement potential was estimated by varying process conditions. Finally, critical process parameters, variables and components for BFP integration were identified and the environmental performance was evaluated using PE factors and CO_2 emission coefficients.

2.1. *Restrictions of the study*

The part load operating characteristics of the BFP process and the dryer were neglected, i.e. has been simulated with a constant specific energy demand. No detailed data on the part-load behaviour of the equipment described in this study could be found in the open literature. It is assumed that the required equipment can operate at somewhat lower loads but the authors are aware that for very low loads (less than 50%), the physical size of the equipment would need to be determined and a two-line approach in which two units would work in parallel in order to represent the required load might be necessary. However, as the focus of the work is on process comparison no detailed component sizing has been carried out.

2.2. *Stand-alone CHP plant and multiperiod model of the district heating network*

2.2.1. *CHP plant*

Process parameters and performance data of the medium-size CHP plant based on bubbling fluidised bed technology have been adapted from Savola [17] and are presented in Table 1. Part-load data of the plant was not available and the plant has been simulated with the commercial thermal power plant simulator Prosim®. An illustrative example of the process is given in Fig. 2a and the actual simulation flowsheet can be found in App. 1a. Prosim® is commercially available software with demonstrated reliability for preliminary design of natural gas and solid-fuel-fired power plants [18]. Prosim® is a sequential modular process simulator and its simulation models are built from process modules and streams. Once the process design is complete and all user data input, the software iterates mass and energy balances by applying the Newton–Raphson method. In design case calculations it also calculates the physical sizes of the selected process modules. Those can be fixed for off-design calculations, i.e. when simulating part-load operation [17].

In order to adjust the simulation model to the data of the DH network the temperature of the bubbling fluidised bed reactor outlet/bed temperature was fixed to 850 °C and the live steam was generated at 60 bars/510 °C. Finally the fuel input was determined in order to achieve a DH output of 16.5 MW at a temperature level of the DH supply and return streams of 83/110 °C matching the full load temperature values as observed from the DH network and explained below. Electricity generation was left as a free variable. For turbine sizing and power output calculation standard turbine curves which are implemented in the software's database have been used. Those represent typical turbine performance curves for different turbine capacities including part-load behaviour. The turbine has been divided into four stages of which the first one is modelled as regulation stage in order to assure constant live steam pressure and turbine speed; the pressure drop in design load is 10%. The second turbine stage is designed in a way that at the assumed minimal possible boiler load which provides 50% of the CHP plant's maximum heat load the pressure will be 10 bars as required by the steam tube dryer that will be integrated (see section 2.3.2). With this arrangement it is possible to show the influence of dryer steam extraction at lower pressures on the BFP integration concept (see section 2.4.1). The last two stages expand the steam to the feedwater tank pressure of 2 bar (where a bleed stream for pre-heating is extracted) and finally to condenser pressure where DH is generated at given temperatures.

Ultimate analysis of the wood fuel assumed in this study has been derived from Phyllis [19] with moisture set to 50%, a typical value for woody biomass [20], see Table 1. The lower heating value has been calculated with the Boie correlation with heat of evaporation of water of 2253 kJ/kg.

The part load operation of the modelled CHP plant have been simulated in off-design mode by adjusting the fuel mass flow in order to reach the user-defined DH load points of 90%, 80%, 70%, 60% and 50%. It is assumed that the bubbling fluidised boiler operation is restricted to a minimum DH load of 50% of the CHP plant's DH design load.

The CHP plant simulation model as described above forms the base-case for comparison to all different process variation described in the following. No further model validation or optimisation has been carried out for the stand-alone CHP plant but based on the suitability of the simulation software the model forms a solid basis for process comparison under part-load condition as it responds realistically on load variations.

2.2.2. *District heating network – multiperiod model*

Real yearly DH network data of a small town in Southern Finland has been used on a daily average basis for representing the connected network's DH load. In order to match the data with the chosen CHP plant capacity, the data was scaled with a constant factor so that the CHP plant provides 60% of the hourly peak demand of the DH network when on full load. The CHP plant is assumed to be shut off at 50% of its design DH load which corresponds with a 30% demand in the DH network. As stated [17], those are common operating parameters for municipal solid-fuel-fired CHP plants. Under those conditions the CHP plants provides 75% of the total yearly DH load which is a typical value [21].

In order to represent the yearly production of the base-case stand-alone CHP plant a multiperiod DH load model was developed, following a method used by Savola [17]. Applying a linear correlation, the DH supply- and return temperatures haven been varied load-dependently from 110 °C to 80 °C and from 83 °C to 36 °C, respectively. Here the highest and lowest monthly average loads are assumed to represent the highest and lowest supply- and return temperature profiles of 110/83 °C and 80/36 °C, respectively. As can be seen in Fig. 1a, two full load and five part load levels (90%, 80%, 70%, 60% and 50%) have been chosen to represent the heat duration curve. The operating hours of the part-load points have been set of equal time and provide the CHP plant's annual DH load together with two full load periods. The full load periods are also of the same duration but differ in their supply and return temperatures in order to represent different outside temperatures during full-load operation. Therefore the full load periods have been split in two of equal duration; one having a supply and return temperature profile of 110/83 °C and the other with a reduced temperature (*r.t.*) profile of 107/79 °C. The two full load periods are later referred to as 100% and 100% *r.t.*, respectively. Simulation models for each load point were run and the fuel input was adjusted in order to match the required DH output, leaving electricity generation as free variable. For calculation of the annual production, DH demand not provided by the CHP plant is assumed to be generated in oil-fired heat-only boilers with a thermal efficiency of 0.93 [22]. Allowing time for yearly maintenance, the annual maximum operation hours have been restricted to 8000 h.

2.3. *The integration concept*

A BFP process was integrated with the CHP process with heat provided by hot flue gases. The objective was to achieve the highest possible BFP product yield with simultaneous retention of the DH load. The BFP process requires a moisture content of approximately 10% [1] and consequently a dryer had to be integrated as well.

2.3.1. *Biomass fast pyrolysis process*

A crucial parameter for modelling BFP is the heat for pyrolysis that consists of the heat required for raising the biomass from starting temperatures to reaction temperature and is complemented by the heat of pyrolysis which is required for the actual (usually) endothermic pyrolysis reaction. In order to estimate the heat for pyrolysis of the woody biomass with its specific composition given in Table 1, a mathematical model was recently developed by the authors [23]. The main assumption of the model is that BFP forms certain chemical groups consisting of carboxylic acid-, aldehyde-, phenol- and

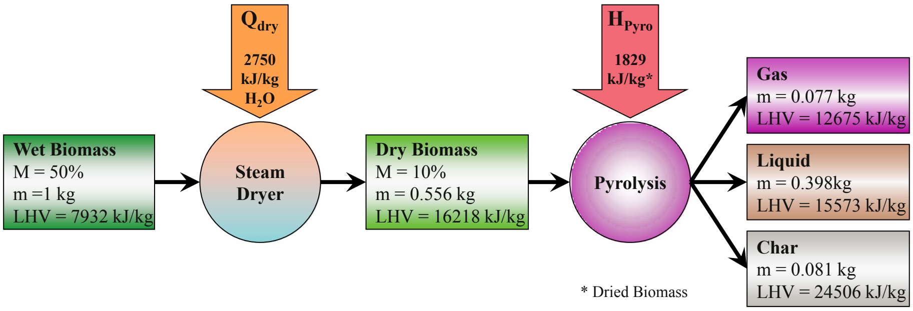

Fig. 3 – Simplified mass and energy balance of the BFP process including drying. *M*: moisture content; *m*: mass; LHV: lower heating value; H_{Pyro}: heat for pyrolysis for heating to reaction temperature and endothermic BFP reaction.

sugar-species along with char, pyrolytic lignin and water. With a more detailed description in Ref. [23] the components presented in Table 2 were used to represent the pyrolysis products. A mathematical optimisation model written in GAMS [www.gams.com] was used to match the molar balance between biomass input and BFP products. In order to achieve that, a certain amount (about 6 wt-%) of hydrocarbon compounds (modelled as pyrene, $C_{16}H_{10}$) was allowed. Starting values were set based on [24] for all components given in Table 2 with an allowed variation of 7.5%. The model was run and the amount of pyrene, which is in reality in the ppm range, was minimised at matching molar balance. The model was run for dry ash-free biomass and the results were corrected with the initial fuel moisture of 10 wt-% (as reached after drying) and the ash content. The start values as well as the final values used are given in Table 2. The water content of the pyrolysis oil was calculated to 23.5 wt-% which is well in range with values given in Ref. [25]. The values estimated with the mathematical model were used in an Aspen+$^{®}$ model in order to calculate the heat for pyrolysis. Therefore a yield reactor was applied with biomass (entered with its ultimate analysis) being converted to the components given in Table 2. The model then calculates the heat for pyrolysis based on the difference of the heat of formation of input and products. The heat of formation of the biomass was calculated based on the heat of combustion which in turn was calculated based on the Boie correlation. With the model, the heat for BFP was found as 1829 kJ/kg. When compared to data measured by Daugaard and Brown [26] the values were deemed reasonable for the biomass assumed in this work. With the data obtained from the Aspen model applying the lower heating value for the chosen components as given by the software and applying the Boie correlation for char and pyrolytic lignin the mass and energy balance of the BFP process (including drying) can be presented as shown in Fig. 3. Based on the lower heating value of the input wet biomass, the BFP process energy yields are 78% BFP oil, 25% char and 12% gases, respectively.

2.3.2. *Retrofit integration of steam drying and BFP with the CHP plant*

The integration concept suggested in this work would use hot flue gases after the actual boiler section as a heat source for the BFP process. As depicted in Fig. 2b, this could be done by opening the boiler casing (3) at the top and connect an additional pass (9) which would be controlled by an induced fan (10) on the cold side after a counter-current sand/flue gas heat exchanger (11). The flue gas would be mixed back to the main flue gas stream (12) before the economiser (8). Even though, the concept is not yet technically proven or applied for BFP processes, controlled bypass of heat exchangers is common practise in large power applications e.g. in order to control the steam re-heat temperature [27,28].

In order to increase efficiency the flue gases should be utilised to as low temperatures as possible. BFP usually takes place at 500 °C, but in real equipment there will always occur a temperature drop through the reactor, i.e. BFP takes place at temperatures around 500 °C. According to personal conversation (R. Stahl, KIT, 2009) a possible temperature range can be that sand enters the pyrolysis reactor (13) at 550 °C for heat provision and leaves the reactor at 450 °C. If a direct counter current heat exchanger is assumed in where flue gases of 850 °C provide the final heating of sand to 550 °C a flue gas exit temperature of 480 °C should be well possible (e.g. downpipe in where sand sinks counter-currently to the ascendant flue gas). Carry-over sand could be minimised by influencing the flue gas velocity and fines would need to be separated with a cyclone (14) and a filter, if required. The pyrolysis reactor could be either of the circulating fluidised bed type or the screw type. Both reactors offer a wide capacity range [2]. After the BFP reactor (13) sand and char need to be separated from the pyrolysis gas by means of a hot cyclone (15). After the separation, the gases are usually quenched in a spray cooler (16) with cool pyrolysis oil in order to achieve rapid cooling for high liquid yields. The permanent gases are co-fired in the boiler. Char and pyrolysis oil can be re-mixed with a colloid mixer (17) to form pyrolysis slurry before transport or further upgrading. The benefit of such an integration concept would be that it should be possible for all common boiler types (bubbling fluidised bed, circulating fluidised bed and grate –fired). The influence of the different boiler types is described and discussed in sections 2.5.2.3 and 3.3.2.3, respectively.

As the received biomass has a moisture content of 50 wt-%, drying is required prior to the BFP process. As hot steam is available and condensate heat can be recovered directly in the feedwater system, provided it is not contaminated, an indirect steam-tube dryer (18) at ambient pressure is suggested in

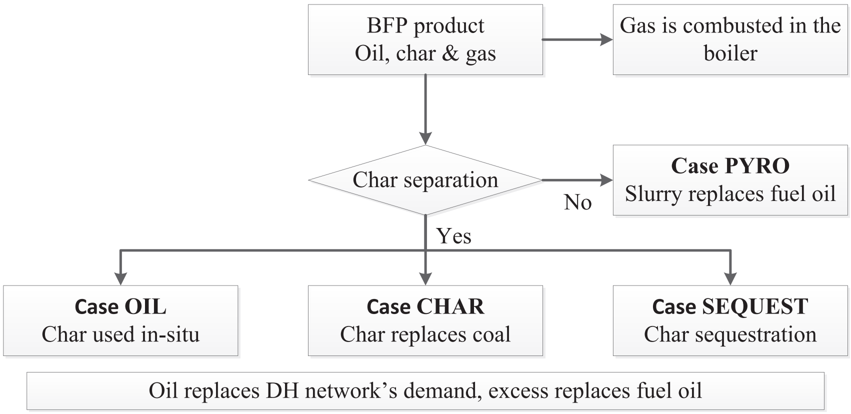

Fig. 4 – Different pathways for BFP product usage.

where the flue gas leaving the air pre-heater (2) is used as carrying medium. The energy consumption of the steam tube dryer was estimated to 3000 kJ/kg water evaporated [20]. If hot enough, the flue gas' latent heat will also be used for drying and the exit temperature of the dryer is set to 143 °C, which is the lowest temperature reached in the CHP stand-alone configuration. Lower flue gas temperatures (approximately 120 °C) might be possible, but 143 °C was chosen in order to allow for fair comparison to the CHP stand-alone process. Heat not supplied by the flue gas will be provided by hot steam. Paying attention to the retrofit situation it was assumed that no changes will be made to the turbine, thus live steam at 60 bar/510 °C is extracted (19), throttled to 10 bar (20) and cooled to 190 °C (21) by the required amount of condensate leaving the dryer. The remaining condensate is rejected after pressure adjustment (22) to the feedwater tank (7) for pre-heating. As a lower extraction pressure for the steam used for drying will increase power generation the potential of adding an additional extraction point to the turbine has been analysed as described in section 2.4.1. After drying, the biomass chips will be comminuted to fine particles with a hammer mill (23) as required for the BFP process.

The retrofitted CHP plant is expected to operate under heavily changed part-load conditions. Hence it is crucial to consider the influence of changed mass flows and temperatures on the heat exchanger and turbine efficiencies. This fact is considered by running the part-load simulations in off-design model with fixed physical sizes for heat exchangers and turbine stages. Regarding the BFP equipment and the dryer, no part-load data is available, but it can be assumed that part-load operation is possible to some extent (50% might be a reasonable value). Regarding the actual process design it would also be possible to run two or more smaller units in parallel that would provide the maximum load only when operated simultaneously. This should be possible for all kind of equipment applied. However for detailed analysis, exact component dimensioning would be required which could be nothing more than an educated guess as literature data for part-load operation of biomass steam-tube dryers and pyrolysis reactors could not be found in the open literature. However in personal discussion (R. Stahl, KIT, 2009) it was mentioned that part-load operation of the applied twin-screw reactor should be possible but has not been tested.

2.3.3. *Implementation of BFP integration with the process simulator – case PYRO*

The flowsheet of the CHP plant integrated with BFP is shown in App. 1b and follows the approach explained in section 2.3.2. The power plant simulator allows easy and reliable part-load calculation of power plant equipment but cannot perform more complex chemical conversion processes such as BFP. As the major interaction between BFP and the CHP plant is the heat extraction from the flue gas, the heat extraction itself is modelled by help of an additional evaporator (see App. 1b, module 26). All other required equipment for pyrolysis has been considered by its power consumption solely (see section 2.3.4). After the integration of BFP and steam drying the DH load is controlled by simultaneous adjustment of the flue gas flow to the sand re-heater, the steam flow to the dryer and, if required, by reducing the fuel input to the boiler. The targeted maximum possible BFP product yield requires the highest possible boiler load since heat shall also be provided to the steam dryer and the BFP process. Conversely, this means that the steam enthalpy flux after the turbine exceeds the demand of the DH network because the boiler temperature is controlled by means of the water/steam mass flow through the evaporator- and superheater tubes in the boiler walls. If the heat input in the boiler at DH part-load conditions is kept on a higher level than actually required, the water amount needed to dissipate the heat from the boiler walls is increased and consequently, in order to match the DH load, this heat must now be consumed in the steam dryer. The DH load was matched by adjusting dryer load, split-off required for BFP and fuel input. The steam dryer's and sand re-heater's consumption are linked, so that all dried biomass can be pyrolysed. With this setup the BFP yield constantly increases with the decrease of the DH levels down to 70%–50% at full boiler load. In turn, the maximum flow off the dryer (and thus its throughput) is restricted by the pressure prevailing in the feedwater tank, which in turn is given by the extraction pressure after the third turbine stage. The pressure decreases with falling live steam parameters and steam mass flow.

Hence, there is a pressure dependant maximum heat flow that can be fed into the feedwater tank until saturation state is reached for the mixture of the condensate from DH exchanger and dryer. In order to overcome this restriction the feedwater tank pressure has been increased load-dependently to a maximum of 2 bars matching its design pressure (it should be noted that for increased pressures no steam is extracted anymore from the turbine). However, due to the reason mentioned above, for loads below 70%–50% the heat that would need to be consumed in the dryer (in order to match the DH load) would result in such a high dryer condensate heat flow, that it would bring the feedwater beyond saturation state. Hence, for those cases the boiler load was decreased gradually. With this control strategy the realisable lowest DH load decreases considerably which leads to an increase in operation hours compared to the base case (stand-alone CHP plant). In all cases the boiler load is restricted to 100%. By this, the overload back-up capacity of the boiler is maintained.

All integration options allow for longer operation hours. This fact has been considered in the multiperiod model of the DH network by firstly determining the lowest possible heat load (later referred to as min) and the related extension in operation hours for the integrated CHP plant. Secondly the average DH load, representing the respective operation time and heat production, was calculated and added as additional load level to the base case scenario, later referred to as subload (see Fig. 1b). The pyrolysis gas combustion has not been simulated but its energy is subtracted from the boiler's fuel input calculated by the simulation software. The influence of the combustion of the pyrolysis gas is described and discussed in sections 2.5.4 and 3.3.4.

2.3.4. *Energy consumption of additional process components*

BFP requires a drier, a twin-screw BFP reactor, a cyclone for solid separation and, following the bioliq® concept of the KIT [29], for pyrolysis slurry production a colloid mixer is needed for slurry preparation. The consumption of the cyclones has been calculated based on the pressure drop through the equipment, which was estimated to 2000 Pa [30]. The steam dryer and hammer mill power consumption was estimated based on [31] as 46.5 MJ/ton wet biomass and 66 MJ/ton wet biomass, respectively. For auxiliary power calculation, the BFP reactor was assumed to be of the screw type and the power consumption was derived from Ref. [32] as 141 MJ/ton wet biomass. Finally the colloid mixer power consumption for slurry preparation was estimated to be 15.2 MJ/ton wet biomass [33]. By that the equipment's total electricity consumption can be estimated to 280 MJ/ton wet wood. The value is subtracted from the net power production as output by the simulation software. For separate use of oil and char the consumption of the mixer has been excluded.

2.3.5. *Use of BFP products*

Regarding the char and oil products, there are different ways for utilisation as depicted in Fig. 4: Following the bioliq® process developed by the Karlsruhe Institute of Technology, the mixture of char and liquid, forming pyrolysis slurry, is considered as final product [4] which will be sold to the market as replacement for fuel oil (case PYRO). Further, oil can be separated from the char and is used to firstly replace the fuel oil used in the DH network's heat-only boiler and any excess is sold to the market as fuel oil replacement. The remaining char can then be used for firing in-situ in the CHP plant (case OIL), can be sold for replacement of coal (case CHAR) or can be considered as a carbon sink and sequestered (case SEQUEST) as suggested by Woolf et al. [7]. The different usage scenarios are presented in Fig. 4 and have been applied only to the basic BFP integration case (case PYRO, see section 2.3.3).

2.4. *Process alternatives*

In the following different process variations are described. The potential of increased electricity production was examined by extracting steam at lower pressures for drying instead of using live steam. Finally the influence of elevated feedwater pressures has been analysed since this parameter seems to be one of the main restriction for higher BFP yields (see section 2.3.3).

2.4.1. *Additional turbine stage – case TURB*

The studied concept is based on the idea that a retrofit application is possible and changes should be restricted to the boiler only. However, lower extraction pressures of steam to the dryer would naturally allow for higher electricity generation since steam enthalpy could then be utilised to a greater extent for power generation prior to being used for drying. Therefore the power plant has been designed with one additional turbine stage (design outlet pressure 43 bars) which is now used for steam extraction. The design pressure of the steam was chosen so that a minimum pressure of 10 bars, as demanded by the dryer, is guaranteed in all operation points. For simulation, the splitter (App. 1b, module 19) has simply been moved from before the turbine regulation stage (App. 1b, module 9) to between stage 1 (App. 1b, module10) and stage 2 (App. 1b, module 11).

2.4.2. *Variation of feedwater tank pressure – cases P**

As mentioned in section 2.3.3, the feedwater pressure limits the amount of biomass that can be dried, since at some point the condensate returned from the dryer heats the feedwater beyond saturation temperature. In order to study the influence of elevated feedwater tank pressures on the BFP yield and the CHP plant parameters, the maximum pressure has been in increased to 2.2, 2.5 and 3 bar, respectively.

2.5. *Sensitivity analysis*

In the following section, it is explained how the main assumptions of the simulation model were varied in order to validate the results. As a major assumption the DH network data has been varied as have the main plant components and structural assumptions. All sensitivity studies are compared to the basic integration described in section 2.3.3 (Case PYRO).

2.5.1. *Variation of the DH load*

As a function of the DH load the operation time values calculated by the multiperiod model and the results of the PE efficiency analysis vary naturally with the heat demand in the DH network. It has been assumed that the maximum and minimum value of the DH demand are absolute values but

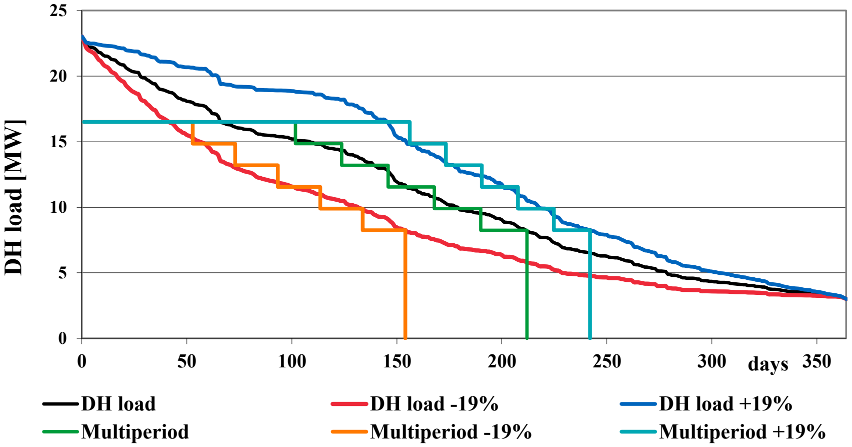

Fig. 5 – Variation of the heat demand in the DH network.

that the gradient of the heat-duration curve would vary as presented in Fig. 5. As only DH data for one specific year was available, the load variation has been calculated based on the following algorithm: as the maximum and minimum values are absolute, the load value of day 182 (of 365) has been varied by 30%. All other values have then been calculated according to the following quadratic equation.

$$q_a = q_i \cdot \left[1 + \left(0.00091x^2 - 0.32967x\right)\right], \tag{1}$$

where q_a and q_i are altered and initial value, respectively. x stands for the day number (0–364) of the heat duration curve. After that the values of the newly generated DH curve have been sorted and plotted as shown in Fig. 5. According to this, the total DH demand changed by ±19%.

2.5.2. *Boiler operation*

The altered assumptions comprise of the assumed minimum load of the boiler, the insertion point for flue gas after heat extraction for the BFP process, as well as considerations regarding the actual boiler design.

2.5.2.1. *Reduction of the minimum boiler load*. Bubbling fluidised bed boiler design is a complex issue due to the many factors influencing the bed regime, such as bed material, pressure, temperature and geometry. Thus, scale-up and -down behaviour are not easy to predict and the assumption of a minimum load of 50% might not hold for all boiler designs, i.e. lower loads might be possible. However, possible lower loads would mean longer operation hours and less free boiler capacity and thus could decrease the potential for BFP integration. Consequently, the minimum boiler load has been decreased to 30% and the corresponding heat duration curve was altered correspondingly.

2.5.2.2. *Flue gas recycling before the superheater*. The influence of feeding back cooled flue gas into the main flow after having exchanged heat to the BFP process before the superheater instead of after it, has been analysed. Referring to App. 1b, superheater 1 (module 5) has been connected directly to the economiser (module 6) and the mixer (module 27) has been placed before superheater 1 (module 5).

2.5.2.3. *Different boiler concepts*. Within a Master's thesis[4] instructed by one of the authors, the influence of a grate-fired boiler on the integration concept was studied. Whereas a bubbling fluidised bed boiler is characterised by constant or nearly-constant flue gas temperatures, the grate-fired boilers flue gas temperature decreases considerably, even by up to 160 °C with decreasing loads. Additionally, the possible boiler concept used by Fortum OY in Joensuu is described, where hot sand leaving a bubbling fluidised bed reactor is used for heat exchange within a second interconnected circulating fluidised bed pyrolysis reactor. Char and sand are vice versa recycled to the first reactor and combusted for heat provision. This heat extraction at high temperatures was expected to have great influence on the steam generation and was approximated by moving the splitter (App. 1b, module 25) before the fluidised bed (App. 1b, module 2) the cooled gases are re-mixed at 850 °C before superheater 1 (App. 1b, module 5).

2.5.3. *Live steam properties*

In order to roughly assess the concept's suitability for smaller CHP stations that are usually characterised by lower feedwater pressures, BFP integration has been carried out for a feedwater pressure of 16.5 bars. The pressures after the two first turbine stages (App. 1b, modules 9 and 10) are reduced in proportion to the live steam pressure whereas the pressures after the two following stages (App. 1b, modules 11 and 13) remain unchanged to assure comparability.

2.5.4. *Influence of pyrolysis gas composition*

As mentioned in section 2.3.3, due to practical reasons the energy content of the produced BFP gas has been subtracted

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[4] Hadera, H., 2011. Biomass based combined heat and power plant with integrated biomass drying and subsequent fast pyrolysis. Master's thesis, The School for Renewable Energy Science, Akureyri, Iceland.

Table 3 – Used PE factors and CO_2 emission coefficients.

	PE factor [–]	CO_2 emission coefficient [kg/MWh]
Biomass	1.09 [34]	14 [34]
Fuel oil	1.35 [34]	330 [34]
Electricity	3.11 [37]	270 [34]
Coal	1.19 [34]	394 [34]

from the required biomass input after the simulation run. In order to see the influence of the real flue gas on the process parameters due to changed mass flows and flue gas heat capacity, a second burner for the BFP gas has been added in parallel to the biomass burner (App. 1b, module 1) to the simulation model. The simulation was carried out for the case of 70% DH load, representing the highest amount of BFP gas fed to the boiler.

2.6. *Process analysis, primary energy efficiency and CO_2 emission coefficients*

For further process comparison the plant's overall thermal efficiency, η_{tot}, has been calculated according to:

$$\eta_{tot} = \frac{Q_{DH} + P + Q_{BFP}}{BM_{in} + FO_{in}}, \tag{2}$$

where Q_{DH}, P and Q_{BFP} are the integrated plant's output in terms of DH, net power and BFP product and BM_{in} and FO_{in} account for biomass and fuel oil, fed to the integrated CHP plant and the DH network's heat-only boiler, respectively.

In addition PE factors and CO_2 emission coefficients with their definition derived from EU standards EN15603 [34] and EN 15316-4-5 [35] have been used for comparison of the different process layouts. In the European standard EN15603 [34] the calculation of energy performance indicators for buildings in general are defined and standard EN 15316-4-5 [35] gives definitions for DH systems in particular. Based on the annual generation data of the DH network, PE factors and CO_2 emission coefficients are calculated applying the power-bonus method [35]. In brief, the sum of all PE inputs to a DH network, divided by the amount of DH delivered is defined as its PE factor. It can hence be understood as a reciprocal efficiency of the DH network (for more details please refer to [36]). Similarly, all CO_2 emitted in order to deliver one unit of DH is expressed by CO_2 emission coefficient. Applying the power bonus method as defined in Ref. [35] the calculation of the PE factor of the DH network (f_{DHN}) is conducted as follows:

$$f_{DHN} = \frac{Q_{BM} \cdot f_{BM} + Q_{FO} \cdot f_{FO} - P \cdot f_P}{Q_{DH}}, \tag{3}$$

where Q_{BM}, and Q_{FO} are the lower heating value-based annual fuel input of wood and fuel oil to the heat-only-boiler and P and Q_{DH} are power and DH generated, respectively. f_{DHN}, f_{BM}, f_{FO} and f_P are the corresponding PE factors. The electricity generated in the CHP plant, by definition, replaces electricity produced elsewhere and f_P is defined as the PE factor of the replaced electricity. It has not been decided yet on a general basis which value to choose and discussion continues but values for power generated in a CHP plant may vary from marginally replacing coal condensing power to national and regional efficiencies of power generation. No guideline is given in the respective standard and thus, in this study, the value of the Finnish average electricity generation efficiency was chosen. The considerable influence of different values for f_P has been discussed in Ref. [37].

In standard EN 15316-4-5 [35] only generation of heat and electricity is considered; thus the power bonus method has been extended by regarding the BFP product as “bonus” too. The PE factor of the BFP-integrated system can then be calculated as:

$$f_{DHN} = \frac{Q_{BM} \cdot f_{BM} + Q_{FO} \cdot f_{FO} - P \cdot f_P - Q_{BFP} \cdot f_{BFP}}{Q_{DH}}, \tag{4}$$

where Q_{BFP} is the heat contained in the BFP-product and f_{BFP} is the PE factor of the replacement. In this study it is assumed that pyrolysis slurry and BFP oil products would replace fuel oil and char would replace coal, respectively. Values and references for the PE factors are given in Table 3 and describe the “energy history” of the fuels (extraction, transport, pre-treatment etc.). CO_2 emission coefficients are calculated accordingly by replacing f in Eq. (4) with the corresponding CO_2 emission coefficient and are given in Table 3.

3. Results and discussion

For all integration options, the results show that stable plant operation is possible without violating material and other operational restrictions. In order to facilitate comparison, Table 4 gives an overview of the simulated cases.

Table 4 – Summary of the simulated cases.

Abbreviation	Description
CHP	Combined heat and power plant without integration
PYRO	CHP plant integrated with steam drying and BFP
OIL	Like PYRO, but char separation, oil for DH network and sale (see Fig. 4)
CHAR	Like OIL, but char for sale (see Fig. 4)
SEQUEST	Like OIL, but char sequestration (see Fig. 4)
TURB	Like PYRO, turbine bleeding for steam drying (see section 2.4.1)
P2.2	Like PYRO, feedwater tank pressure max. is 2.2 bars (see section 2.4.2)
P2.5	Like PYRO, feedwater tank pressure max. is 2.5 bars (see section 2.4.2)
P3.0	Like PYRO, feedwater tank pressure max. is 3.0 bars (see section 2.4.2)

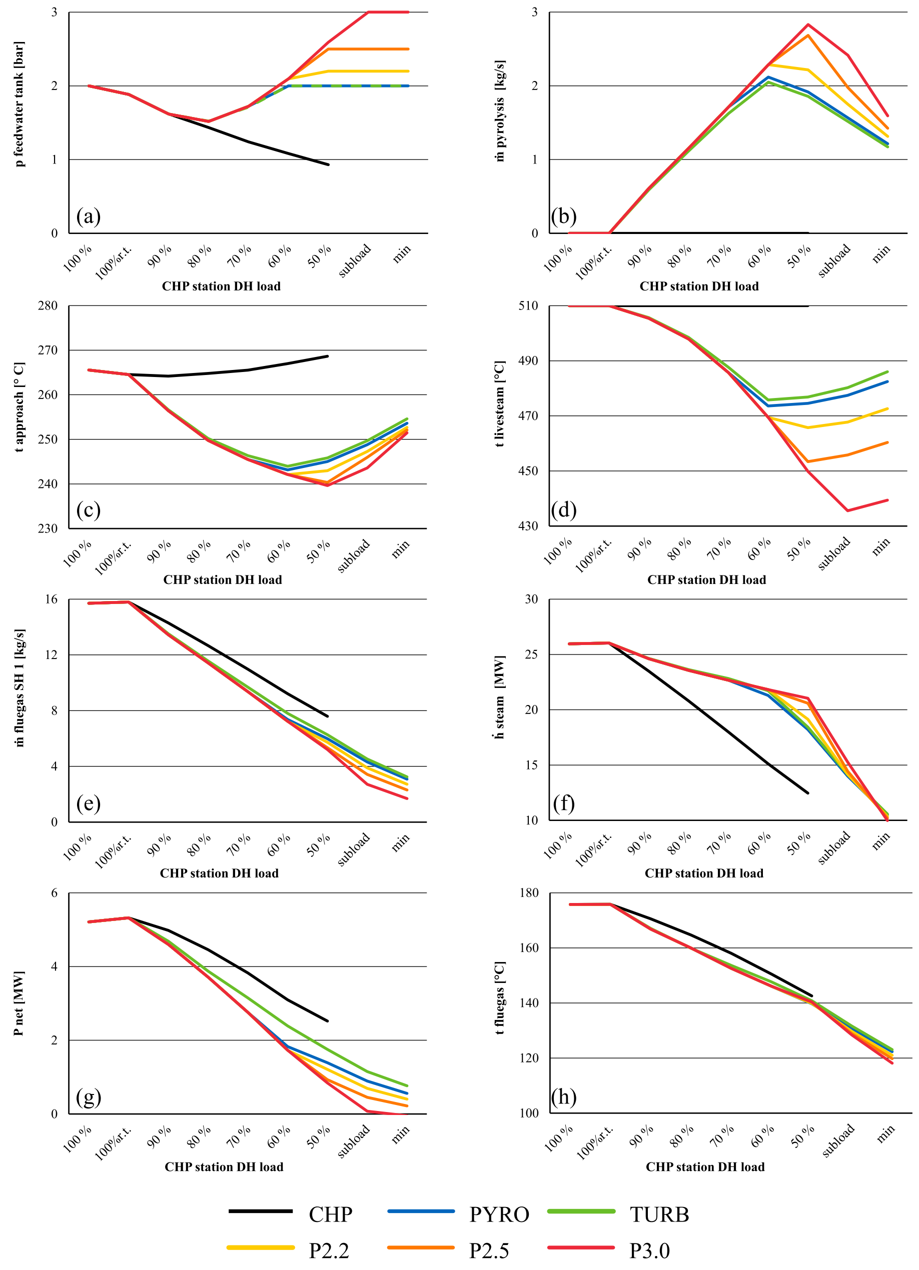

Fig. 6 – Comparison of selected plant operation parameters.

3.1. *Operational parameters*

As mentioned above all integration options are possible within the operational limits of the CHP unit. As can be seen in Fig. 6a, the pressure in the feedwater tank increases with increasing BFP loads (see Fig. 6b). This is due to the increasing condensate flow from the dryer. The dryer operates at 10 bars and the condensate has a considerable enthalpy, which would, at lower pressures, bring the water in the feedwater tank beyond saturation temperature. It can be clearly seen that higher BFP yields come with higher feedwater pressures. It can be observed that the approach temperature to the boiler which is designed to be 10 °C below saturation decreases for all integration cases (Fig. 6c). This can be attributed to lower flue gas temperatures after heat extraction for pyrolysis for all equipment following the boiler. Interestingly, increased feedwater tank pressures (leading to higher temperatures after the feedwater tank) do not increase the boiler approach temperature. Conversely, higher pressures of the feedwater tank show the lowest approach temperature, stemming from the fact that in those cases also dryer and pyrolysis load are at the highest leading to lowest flue gas temperatures before superheater 1 and economiser. It can be concluded that elevated feedwater tank pressures increase the BFP yield.

In continuation it can be observed, regarding the live steam temperature (Fig. 6d), that all integration options decrease the

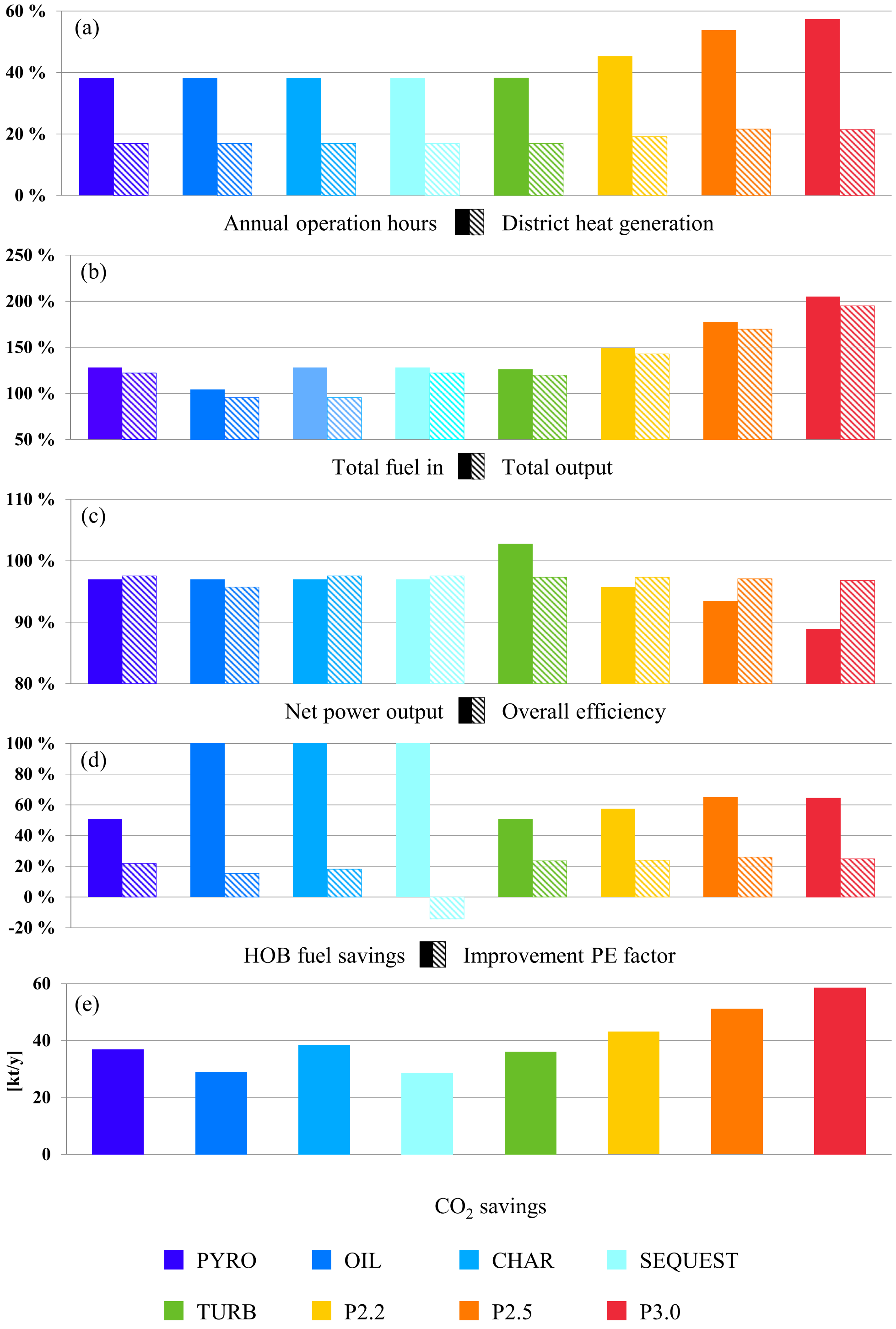

Fig. 7 – Operational and environmental performance of the different integration options. (a): Percentaged change of yearly operation hours and DH generation relative to the base case CHP plant. (b): Percentaged increase of fuel in and total product output (power, heat, BFP output) relative to the base case CHP plant. (c): Percentaged net power output and overall efficiency relative to the base case CHP plant. (d): Percentaged change of fossil fuel input to the DHN and DHN's PEF relative to the base case CHP plant. (e): Total yearly CO_2 saving potential calculated according to EN 15603 and compared to the base case CHP plant.

live steam temperature, some of them even by 75 °C. The main influence on the temperature decrease is the amount of biomass that is pyrolysed, since it defines the amount of flue gas that is split off after the boiler and fed back cooled after the first superheater. The lower flue gas mass flow (Fig. 6e) through the superheater naturally reduces the degree of superheat reachable in it. The lower mass flow deteriorates the efficiency of the heat exchanger resulting into a lower amount of heat transferred. As the steam mass flow required to maintain the boiler temperature is not changing, it means that the degree of superheating reached in the first superheater is not sufficient for reaching full superheating after the second stage. Although the temperature and hence the related drop in the specific enthalpy of the live steam can be compensated by the much higher mass and thus enthalpy flux compared to the base case (Fig. 6f), the net power output decreases (Fig. 6g). This is due to the auxiliary power consumption used by the additional equipment. For a feedwater pressure of 3 bars at very low loads power generation can become slightly negative, i.e. power would need to be purchased in order to run the BFP equipment.

Critical analysis is further needed for the flue gas temperatures after the air-preheater (Fig. 6h). In all simulation cases, for loads below 60% temperatures dropped below the base case of 144 °C with temperatures as low as 118 °C. Depending on the fuel composition, potential corrosion problems need to be ruled out. It must be mentioned that for comparison the flue gas outlet temperature after the dryer was fixed to 144 °C. With lower temperatures somewhat higher pyrolysis slurry yields could be reached.

3.2. *Energetic and environmental analysis*

The energetic and environmental performance has been evaluated based on the results of the simulations. Additionally, the performance has been evaluated by applying the PE method described in section 2.6.

3.2.1. *General energetic and environmental performance indicators*

Regarding the performance of the integrated plant, Fig. 7a shows that the yearly operation hours can be increased by up to 57%, corresponding to 8000 h, which was defined as the maximum possible. The maximum operation hours are achieved for high feedwater pressures allowing high dryer and thus BFP throughput as explained in section 2.3.3. The additional turbine stage (TURB) as well as different usage options for the BFP products have no influence on the operation time.

As presented in Fig. 7b, all integration options increase the plant's total output by 95%–195% when compared to the base case CHP plant. The different pathways of BFP product use (in blue-scale) clearly shows the fuel input reduction for the case where BFP oil would be the only product-the char would be combusted in the bubbling fluidised bed boiler and hence reduces its wood fuel input. Changes on the turbine result in small reductions in both, input and output. As expected the increased feedwater tank pressure allows highest biomass throughput indicating that high pressures should be achieved.

Fig. 7c shows the influence of the BFP integration on the annual net power output of the plant and the overall efficiency calculated according to Eq. (2). Despite the case TURB, where annually 1.2 GWh additional power can be generated, no integration option can compensate for the power consumption of the auxiliary equipment. Neglecting added auxiliary consumption, all cases would allow for a higher net output based on the extended operation hours. It can also be seen that the overall efficiency is slightly deteriorated as a result of the slightly lower efficiency of the BFP process compared to the stand-alone CHP process. This especially affects lower loads, where the overall efficiency of the CHP increases due to reduced exhaust temperatures.

3.2.2. *Primary energy efficiency and CO_2 emission analysis*

In Fig. 7d it can be seen that all integration options, except one, have the potential to improve the PE efficiency considerably by approximately 20%. The best value can be achieved for increased feedwater pressures of 2.5 bars due to a favourable ratio of power and BFP product generated and relatively long operation hours. In the case of a feedwater pressure of 3 bars, operation hours are longer (see Fig. 7a) but also power generation, which is rated with a high PE factor, decreases. Interestingly, the sequestration of the BFP char impairs the PE factor; this is due to the fact that the sequestered char has no power bonus, since it does not constitute a replacement. Thus, sequestration does not save PE but increases the demand for it, due to the unutilized energy in the sequestered carbon. Fig. 7d also shows the reduction in fuel consumption required by the heat-only boiler. The heat-only boiler's fuel consumption constitutes one of the inputs for the calculation of the PE factor of the DH network considered. The reduction can, for all cases, be partly allocated to the longer operation hours. Integration allows for the supply of lower DH loads by offering an additional heat sink. It can also be seen from the graph that, provided the equipment will be adapted for combustion of BFP oil, the whole DH network considered could be supplied by the CHP solely. However, this allows less improvement in terms of PE efficiency and hence it can be concluded that for highest PE efficiency the BFP product should be used for replacing fossil fuel, i.e. the co-generated product should be rather sold to the market than consumed on-site.

For presentation of the CO_2 savings, CO_2 emission coefficients have been calculated as described in section 2.6. The factors (unit: kg/MWh_{DH}) have then been multiplied with the amount of DH generated in order to determine the CO_2 saving potential in kt per year. The results are presented in Fig. 7e and show that long operation hours with high BFP yield, like in the cases of increased feedwater tank pressure, is also most beneficial for CO_2 mitigation since a high amount of fossil energy can be replaced. Regarding the different use

Table 5 – Influence of the variation of the DH load on the yearly performance values.

Case	DH output [GWh/y]	Power output [GWh/y]	Pyrolysis slurry output [GWh/y]	Operation hours [d/y]	PE factor [–]	CO_2 emission factor [kg/MWh]
CHP	70.8	22.9	–	212	1.11	52
CHP high DH	85.6	27.5	–	242	1.06	38
CHP low DH	49	15.8	–	154	1.38	117
PYRO	82.8	2223	103.2	293	0.87	–393
PYRO high DH	96.9	27.3	87.4	318	0.88	–285
PYRO low DH	63.9	15.8	109.3	256	0.94	–520

of the BFP product (in blue-scale), it can be concluded that replacing coal with biochar (case CHAR) is the best strategy for reducing CO_2 emissions. This stems from the fact that the emission bonus for coal replacement is higher than for fuel oil which is applied in the case of pyrolysis slurry. Co-firing the char in the CHP plant (case OIL) appears less beneficial with the analysis method applied. However, for final evaluation one would need to consider also CO_2 emissions occurring during transport of the char. Also sequestration of char is not beneficial, due to the low amount of CO_2 that could be allocated for this approach-only the CO_2 that would have been emitted during char combustion has been accounted as benefit.

On a broader perspective the results further indicate that the different options would lead to CO_2 reductions ranging from 30 to almost 60 kt per year, provided the products replace the fossil counterparts according to the assumptions made in section 2.6. It is remarkable that with a plant sized approximately 35 MW the Finnish annual CO_2 emissions could be reduced by 0.05%–0.11%. Considering the potential of currently unused forest material in Finland of about 16.4 TWh as well as a projected potential of CHP units of 5–8 TWh, the integrated concept could reduce annual CO_2 emissions considerably, by 5.7% provided that all available biomass would be utilized in BFP-integrated CHP plants. Although these figures provide only a rough estimation, it still shows the considerable potential of such integrated concepts.

3.3. *Sensitivity analysis*

In the following section the results on the variation of the main parameters influencing the performance of the integrated plant are presented. It can be said that changes in the DH demand have a considerable effect, but that integration appears beneficial for a wide variation range representing extremely warm and cold years. With the chosen modelling approach, the boiler operation has minor influence on the results, as has the consideration of the real composition of the BFP gas compared to the simple subtraction of the gas' energy content from the boiler input. Lower design steam parameters, as they are likely to appear in smaller installations seem to not impede the benefit of the BFP integration.

3.3.1. *Variation of the DH load*

As shown in Table 5, the variation of the boiler load for the base case leads naturally to 14% increased and 27% reduced operation hours for the higher and lower DH demand, respectively. BFP integration in both cases allows for a 31% and 66% increase in operation hours. The net power output for the higher DH demand (PYRO high DH) is, as for operation at design DH load (PYRO) slightly lower due to the power consumption of the additionally installed equipment. Due to a sharp increase of operation hours in the case of low DH demand this penalty can be overcome and losses caused by the additional equipment can be compensated for. The PE factor can be clearly improved by 17% by BFP integration in the case of a higher DH demand. For lower DH loads the benefit is even higher and turns a worse PE factor of the base case (PE factor = 1.38, resulting from a low power to heat ratio) into a clear improvement. More interestingly, also the CO_2 emission coefficient can be clearly improved, owing to a very beneficial product distribution. In summary, it can be said that BFP integration improves the performance of the CHP plant in all operation situations and is particularly beneficial in years with DH loads lower than the design load. This might be important for the future when DH load can be expected to decrease due to improved building insulation (e.g. net-zero energy buildings).

3.3.2. *Boiler operation*

3.3.2.1. *Reduction of the minimum boiler load*. Applying the concept to a boiler which in design load would be able to operate at loads down to 30% of its design load results in about two months of increased operation time (67 days). Consequently the improvement by BFP integration turns out smaller and accounts for only 20%, due to the maximum yearly operation hours being restricted to 8000. But still, the total output (heat, power and pyrolysis slurry) can be increased by 113% with a similar increase of the total input. Also PE factor and CO_2 emissions are influenced positively by 19% and CO_2 mitigation can be as high as 39 kt per year.

3.3.2.2. *FG in short circle*. The change in the feedback point of the cooled flue gas after heat exchange with the BFP reactor influences the analysed data only in small ranges of less than one per cent. As could be expected, the main influence is on the live steam temperature where the temperature drops by 5 °C due to mixing before the second superheater. This owes to the lower heat exchanger efficiency at lower flue gas temperatures. In the following the change leads to a slight change in the product distribution yielding less power (–0.5%) and more BFP product (+0.3%).

3.3.2.3. *Different boiler concepts*. As for the change in flue gas recirculation, it has been found that changes in the boiler result in minor influences on operation and performance of the integration concept. No operational problems could be found. The three different simulated boiler concepts have no influence on the operation time and, consequently, do not affect the generated DH. Being a result of the slightly higher steam temperatures when heat is extracted at high temperature, fuel input, power output and BFP product output are 2.3%, 2.7% and 2.4% higher, respectively, than for the case of a radiant furnace case. The bubbling fluidised bed case with heat extraction after the boiler (Case PYRO), on which all the other study's result are based ranks in between, but closer to the radiant furnace case. However, PE factor and CO_2 emission coefficient do not differ between the fluidised bed cases but are somewhat higher for the radiant furnace case. This represents the efficiency benefit associated to fluidised bed reactors when compared to grate-fired boilers.

3.3.3. *Live steam properties*

For lower live steam parameters of 16.5 bars and 400 °C the increase of operation hours and fuel input is in the range of the other cases discussed (35% and 120%, respectively). However, due to the lower live steam pressure and temperature the loss in power is higher and accounts for 10%. Due to the lower process efficiency the PE factor of the base case drops by 22% from 1.11 to 1.35, but can be improved to 1.12 by BFP integration. Hence, also this improvement of 20% is in the range of the results obtained before. The same accounts for the CO_2 emissions that can be mitigated by 38 kt annually. In conclusion, BFP integration seems beneficial for smaller plants with lower steam parameters.

3.3.4. *Influence of pyrolysis gas composition*

The influence of the actual BFP gas on the analysed process parameters is small, i.e. in the range of 1–3% affecting the flue gas temperatures the most but the live steam temperature to a small extent too (−1%). This is due to slightly higher combustion temperatures for the biomass/gas mixture, which leads to higher steam mass flows in the boiler. In addition the heat capacity of the flue gas decreases somewhat due to a lower water content and causes the slightly lower live steam temperatures.

4. Conclusions

The integration of BFP within a CHP plant is found possible for all operation points. Attention should be given to the exhaust temperatures after the air-preheater since those can drop to temperatures below those reached in stand-alone operation. The steam dryer should be designed for low exhaust temperatures in order to use a high amount of heat available from the flue gases that are used as a carrier medium. Adaption of the turbine extraction nozzles bears some improvement potential and can help to compensate power losses caused by the additionally installed equipment, but cost-effectiveness needs to be proven. Due to lower possible DH loads, integration enables the increase of operation hours by up to 57%. If possible the feedwater tank pressure should be as high as possible, as this clearly improves the energetic and environmental performance the most. However, the possible reduction in power generation needs to be evaluated carefully in order to avoid a negative power balance for BFP operation. Only for the power generation the higher feedwater pressure is not optimal since more biomass throughput also requires more steam to the dryer leaving less to the turbine. In order to increase the pressure after the dryer an additional direct mixer could be installed as well, reacting on safety and material restrictions set by the original feedwater tank. Due to the lower efficiency of the BFP process compared to the stand-alone CHP, the overall efficiency being an average of the individual processes' efficiencies slightly drops. Regarding the uses of the product it can be concluded that as much product as possible should be sold to the market as it clearly improves the DH networks's PE efficiency and CO_2 savings. However, this result is heavily depending on the assumptions made for the PE factor of the replaced energy form. It can also be said that with the evaluation method applied sequestration of char is not more beneficial concerning potential CO_2 saving and turns out to be a bad choice regarding the efficient use of primary resources. However, the mid-term CO_2 storage effect achieved by the sequestration of the char has not been accounted for. In total, the integrated small-to medium sized plant has the potential to mitigate CO_2 emissions by up to 60 kt annually which equals 0.11% of the total Finnish emissions. It has further been concluded that the integration's benefit can also be accounted for in years with considerably higher and lower DH demand. It has also been shown that different boiler concepts and sizes can be integrated with none of them showing critical or unbeneficial behaviour. The co-firing of pyrolysis gas is found to have minor influence on the CHP plant's thermal balance.

Summarising it can be concluded that integration of BFP with CHP plants is thermally possible and beneficial regarding the energetic and environmental performance. If indirect steam drying is applied the condensate should be fed back at as high pressures as possible. With this strategy future CHP plants will be able to provide valuable products at high efficiency and also help mitigating global CO_2 emissions.

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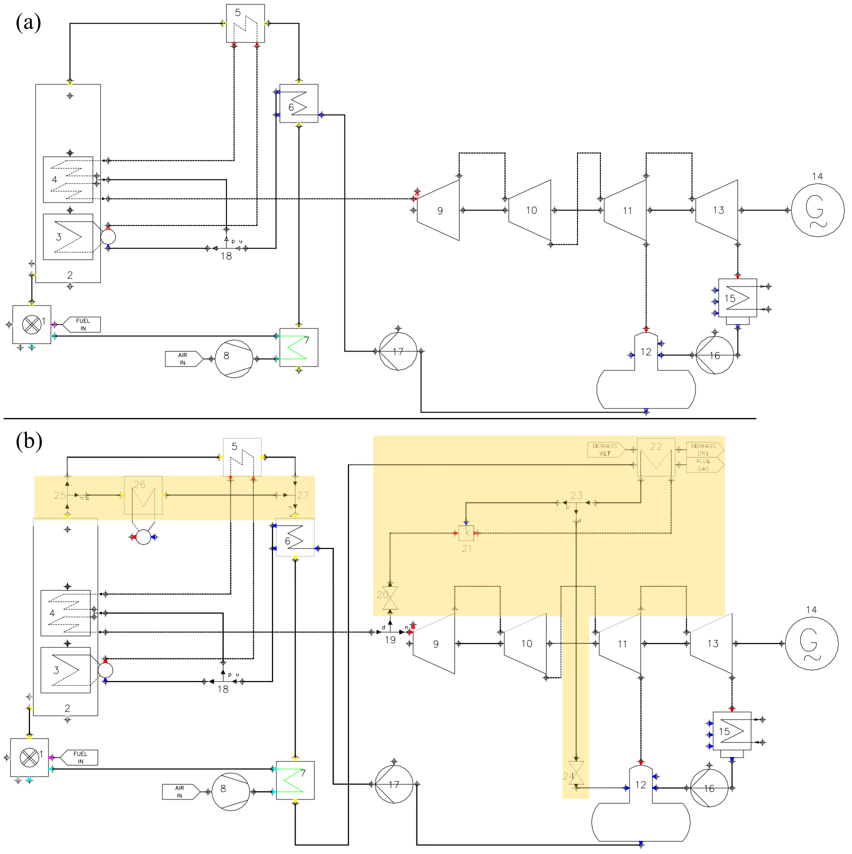
Appendix A



1 Burner
2 Fluidised bed
3 Evaporator (in bed)
4 Superheater 2 (in bed)
5 Superheater 1
6 Economiser
7 Air pre-heater
8 Air blower
9 Regulation stage
10 Turbine stage 1
11 Turbine stage 2
12 Feedwater tank
13 Turbine stage 3
14 Alternator
15 DH exchanger
16 Feedwater pump 1
17 Feedwater pump 2
18 Regulation valve
19 Splitter
20 Throttle valve
21 Spray cooler
22 Indirect steam dryer
23 Splitter
24 Throttle valve
25 Splitter
26 Evaporator (BFP)
27 Mixer

Appendix A. Flowsheet of the simulation model of (a) the stand-alone CHP plant and (b) CHP plant integrated with steam drying and BFP. The differences in the process layout between BFP-integrated plant and the base case CHP plant are highlighted.

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